Space-Based Ionosphere-Thermosphere Research Conference
October 18 2007

Remote Sensing of the Ionosphere and Plasmasphere from Space Using Radiowaves

Anthony J. Mannucci
Jet Propulsion Laboratory
California Institute of Technology

Topics

- Why bother…the scientific context
- Trans-ionospheric and sounding
- Small-scale structure
- Plasmasphere
- Tomography: “fast” and “slow”

- Pseudo-imaging

Where Geospace Science Stands Today

- Characterization of ionospheric behavior has changed dramatically in the past 10 years
  - Including mid-latitudes
- We can now identify large to meso-scale plasma structures that vary over time scales of minutes to hours
- New phenomenology has been discovered

Missing:

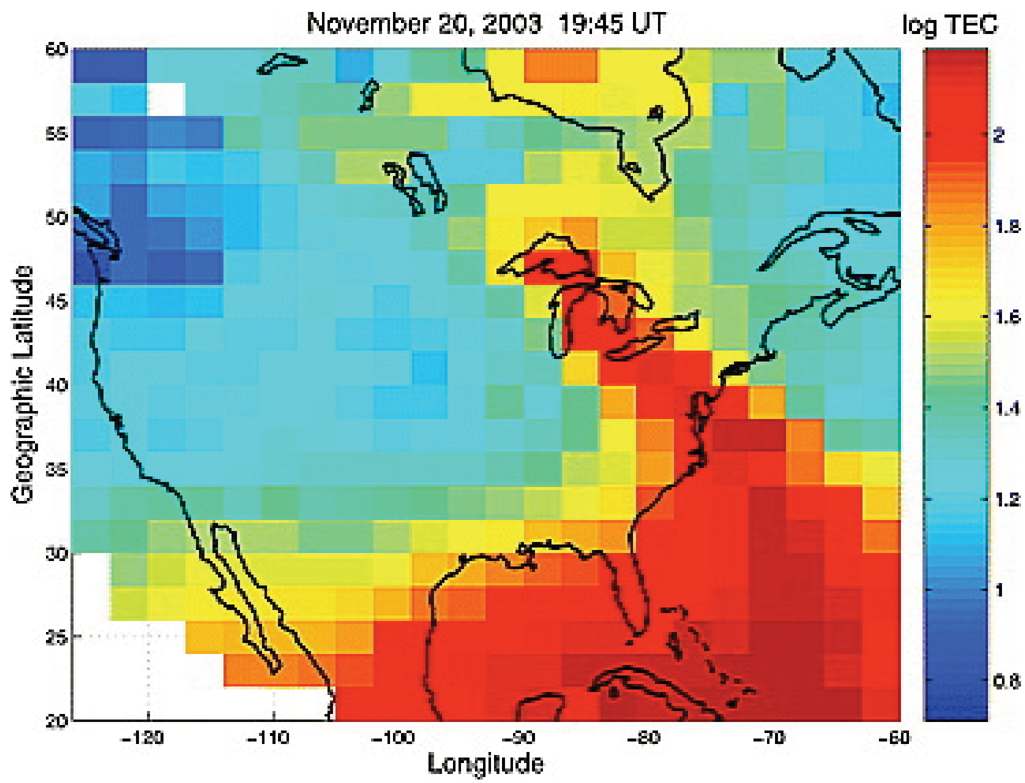
- The right observations at the right locations to achieve *understanding* of what is observed

Highest scientific priority:

- Achieving understanding

Variability: Inner Magnetospheric Electric Fields

Foster et al, JGR, 2005



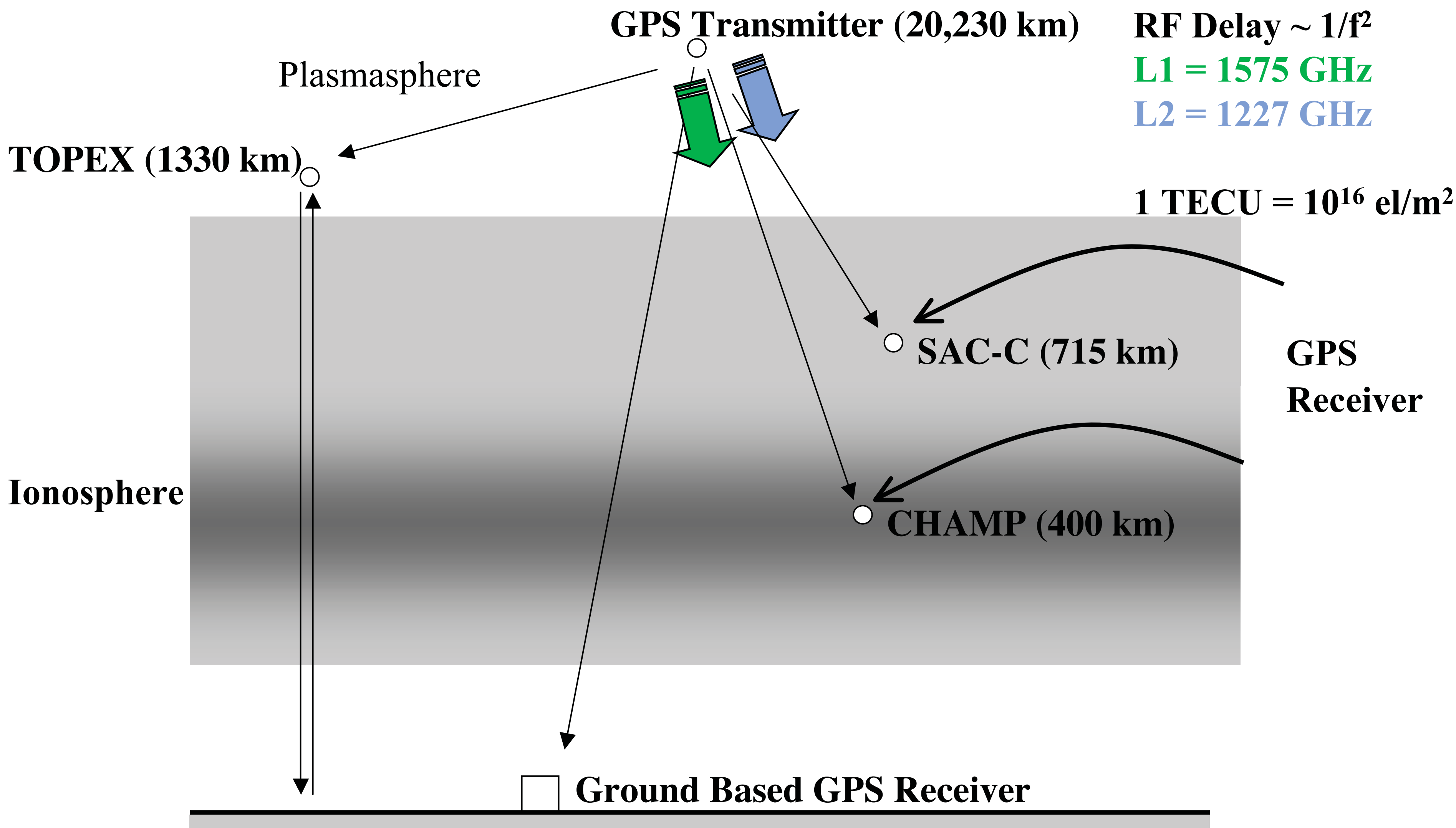
GPS TEC data

Dusk effect

The expansion of the convection pattern can transport middle latitude plasma to high latitudes.

Here plasma from below 50 degrees magnetic is transported poleward and across the high latitude regions.

This feature would not be easily visible if there were not a high density reservoir from which the plasma were extracted. (**where does this come from ?)**


GPS Transmitter (20,230 km)
RF Delay ~ 1/f²
L1 = 1575 GHz
L2 = 1227 GHz
Plasmasphere
TOPEX (1330 km)
1 TECU = 10¹⁶ el/m²
SAC-C (715 km)
GPS
Receiver
Ionosphere
CHAMP (400 km)
Ground Based GPS Receiver

Appleton-Hartree Formula

$n_{\pm}^{2}=1-\dfrac{2X(1-X)}{2(1-X)-Y_T^2\pm\sqrt{Y_T^4+4(1-X)^2Y_L^2}}$ $X=\left(\dfrac{f_p}{f}\right)^2=\dfrac{\left(n_p e^2/4\pi^2\varepsilon_0 m\right)}{f^2}$ $Y_T=Y\sin\theta_B;\quad Y_L=Y\cos\theta_B$ $Y=\dfrac{f_g}{f}=\dfrac{\left(\lvert e\rvert B_0/2\pi m\right)}{f}$	Appleton-Hartree: electromagnetic wave (carrier) propagating in a magnetized plasma, neglecting collisions

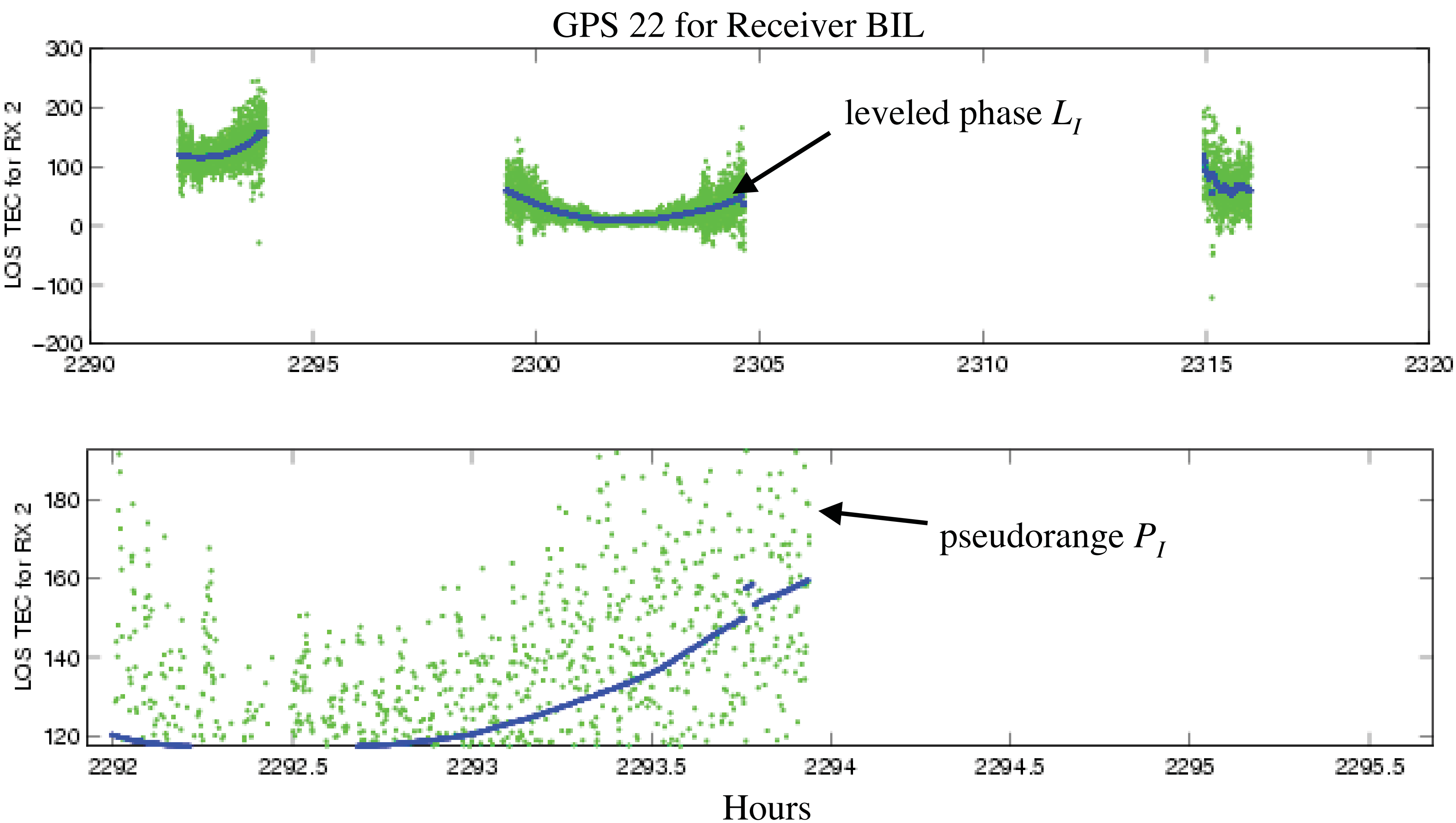
$n_{\pm}^{group}=1+\dfrac{1}{2}X\mp XY\lvert\cos\theta_B\rvert+\dfrac{3}{4}X\left[\dfrac{1}{2}X+Y^2\left(1+\cos^2\theta_B\right)\right]$	Using (6) above

Phase and Range Ionospheric Observables

$PI = P_2 - P_1 = 40.3TEC\left(\frac{f_1^2 - f_2^2}{f_1^2 f_2^2}\right) + b_I^r + b_I^s$ $LI = L_1 - L_2$ $= 40.3TEC\left(\frac{f_1^2 - f_2^2}{f_1^2 f_2^2}\right) + n_1\lambda_1 + n_2\lambda_2 + b_I'^r + b_I'^s$	First-order delays, with interfrequency biases included

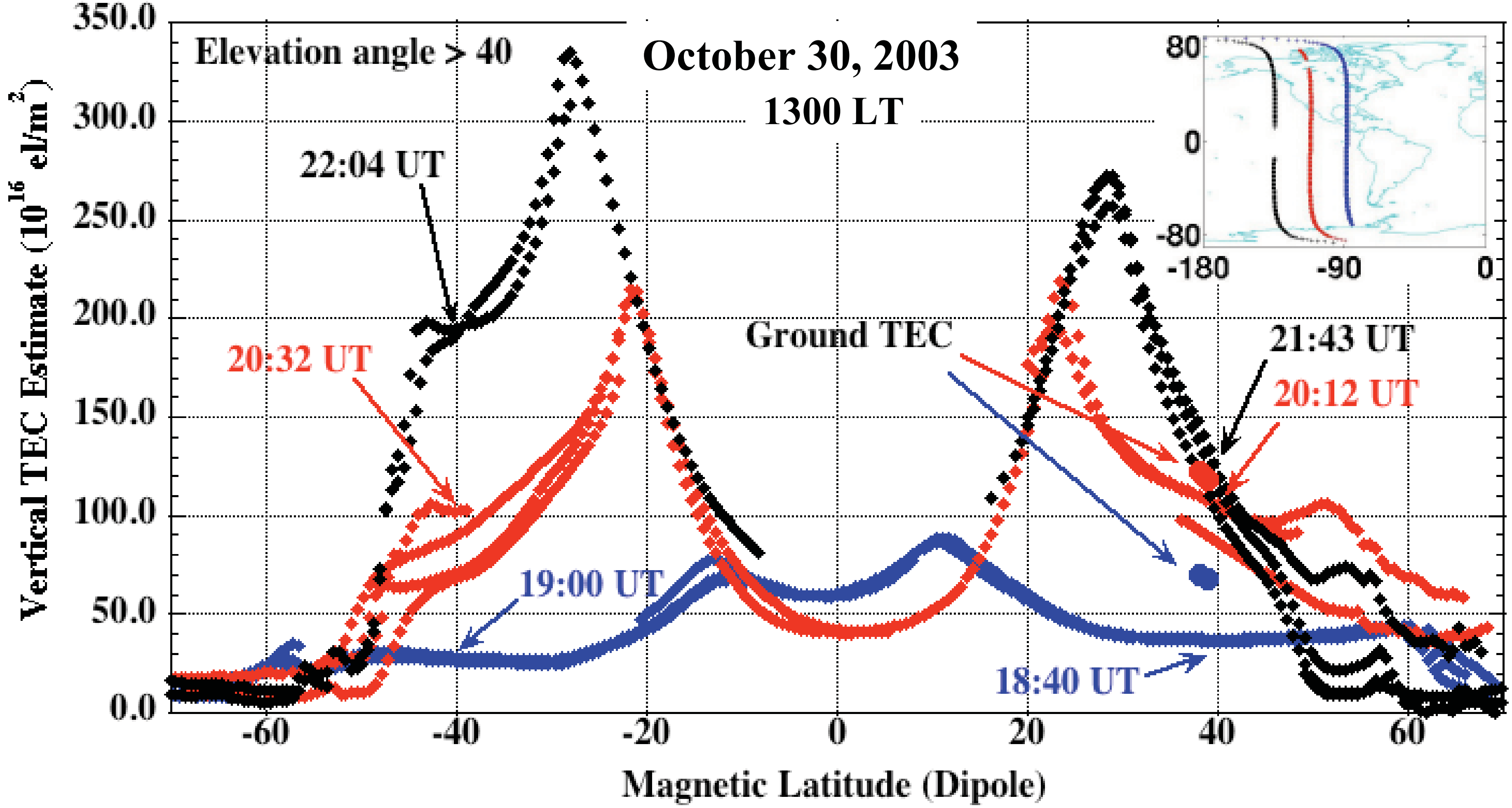
- **In direct TEC observations (single-difference), phase level is assumed unknown**
- **Pseudorange level is absolute, except for instrumental biases**
- **Pseudorange noise >> carrier phase noise**

Examples of Leveling



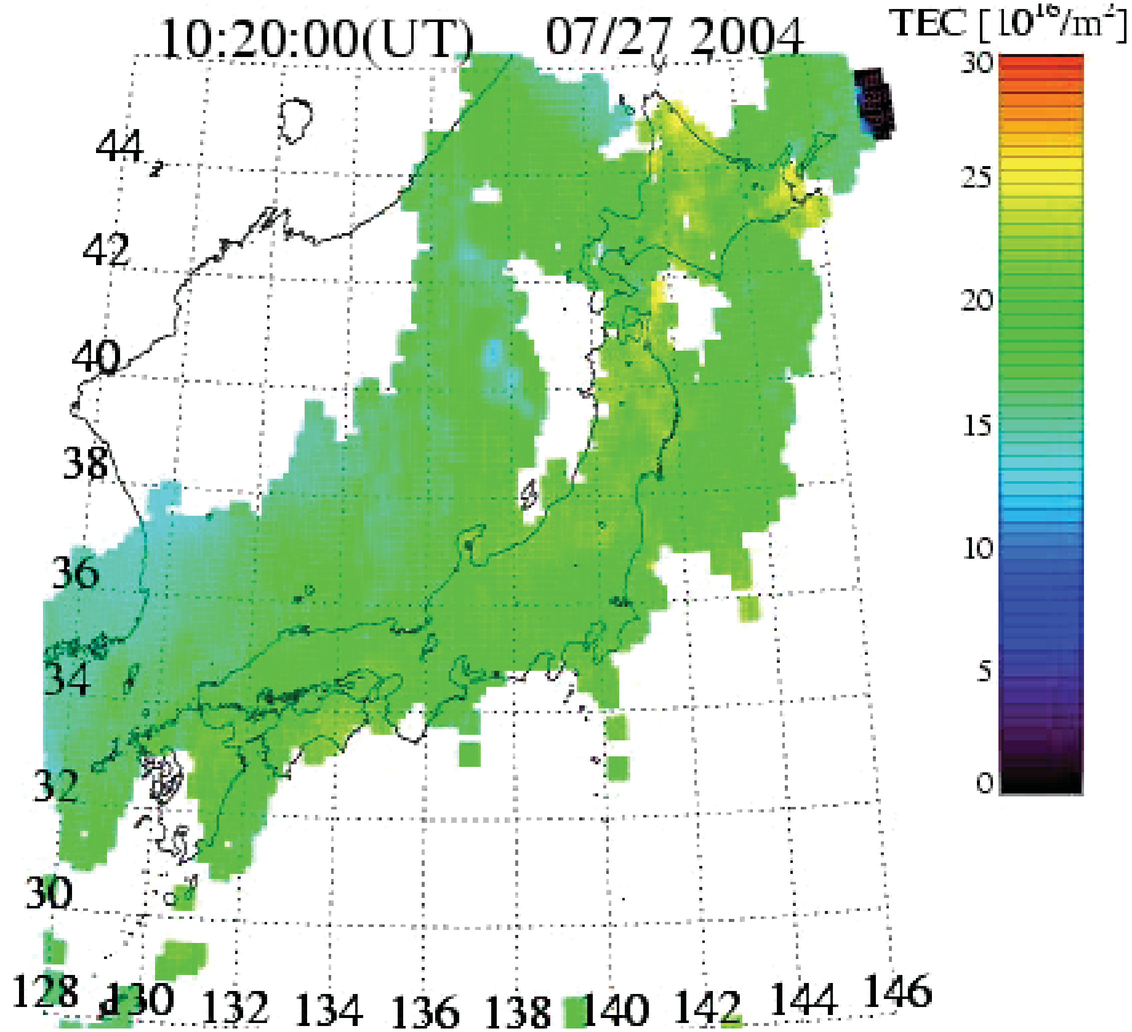
Large Ionization Changes During Storms

CHAMP (TEC above 400 km altitude)



Mannucci et al., GRL 2005

New Mid-Latitude Phenomena

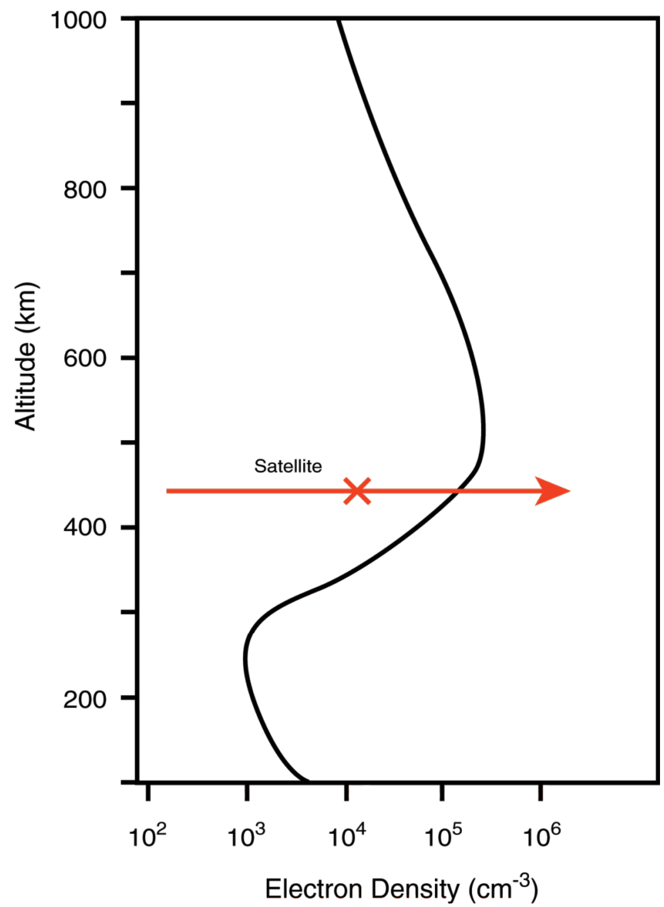


Ionospheric Sounding
Probes that gather data along satellite trajectory

- *In situ* probes (e.g., Langmuir probes) on satellites are straightforward, reliable, and provide accurate measurements of both plasma density and structures/irregularities along the satellite path.

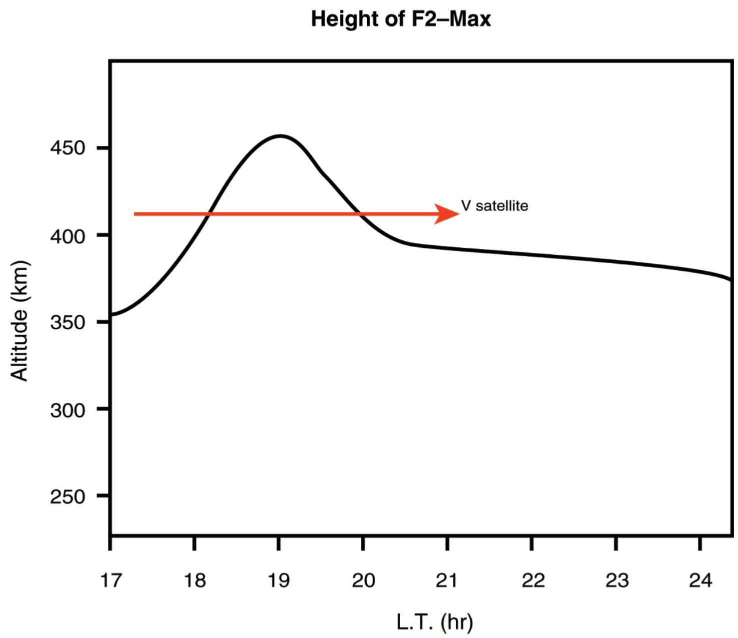
- The peak density and its altitude are not known. Indeed the probe could be above or below the F-peak.

- Knowledge of how the F-peak varies in altitude and amplitude is often the key to understanding the large scale behavior of the ionosphere.



Gathering knowledge of the F-peak along the satellite trajectory…

- Satellite track could be above or below the F-peak, particularly as the ionosphere changes with local time, latitude.
- Shown is drawing of an equatorial satellite trajectory such as C/NOFS.



- Space-based sounders that provide the F-peak density profile both *above* and *below* the satellite enable a new window on ionospheric measurements.

-- Scientific satellites with in-situ probes must go where the physics is, which is usually to lower altitudes (200 - 500 km), particularly where neutral atmosphere/ionosphere processes are studied.

-- The F-peak information along the trajectory can be readily compared to the other measurements gathered *in situ*, such as neutral winds, electric fields, currents, ion composition, etc.

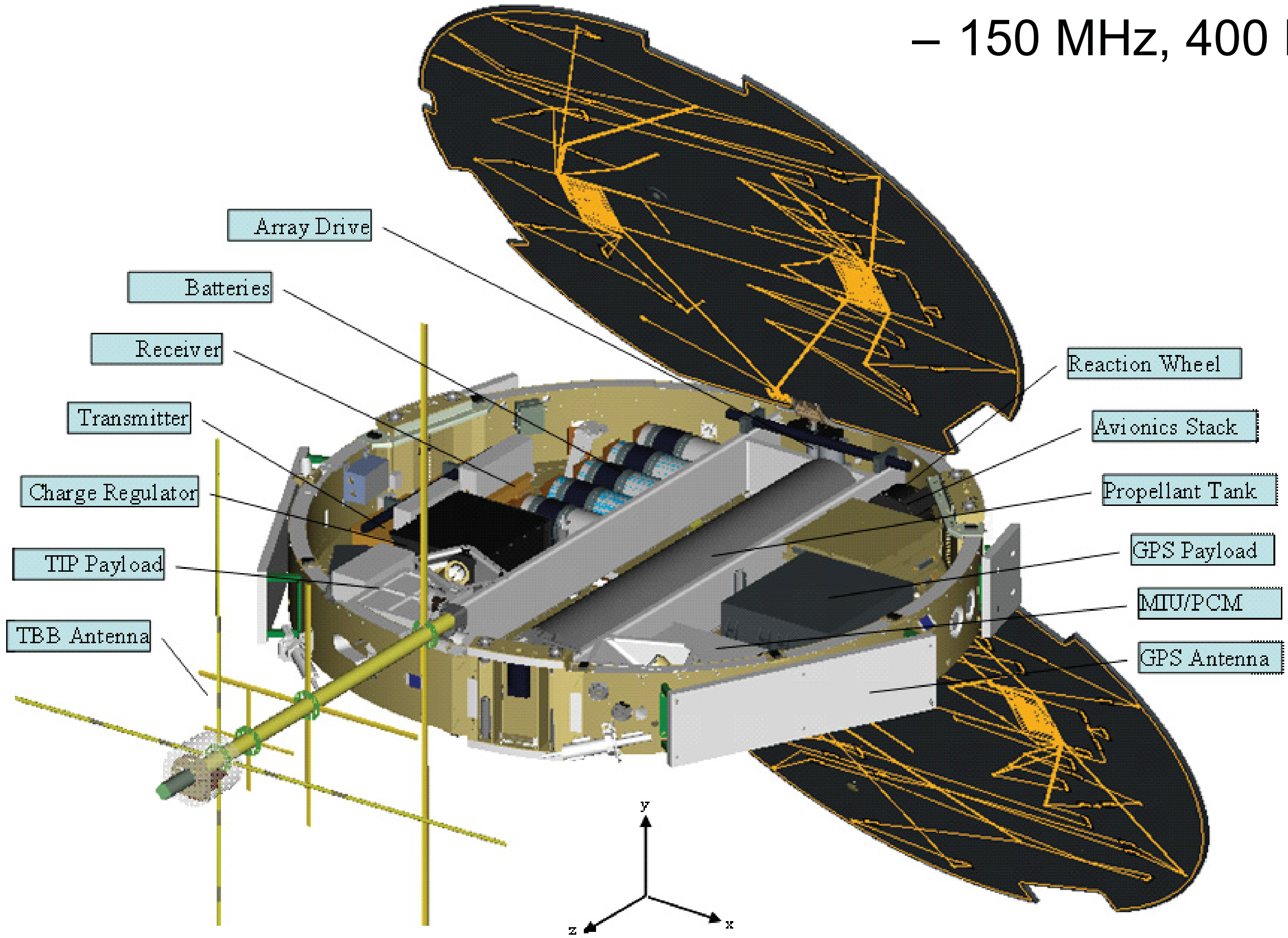
Ionospheric Sounding

- **Ionospheric sounding from 450 km altitude provides accurate electron density profiles to hmF2**
- **Determines whether S/C is above or below hmF2**
- **Advanced space-borne sounder designs exist**
- **Software for automatic analysis exists**
- **Low radiated power using DSP**

More later in the program…

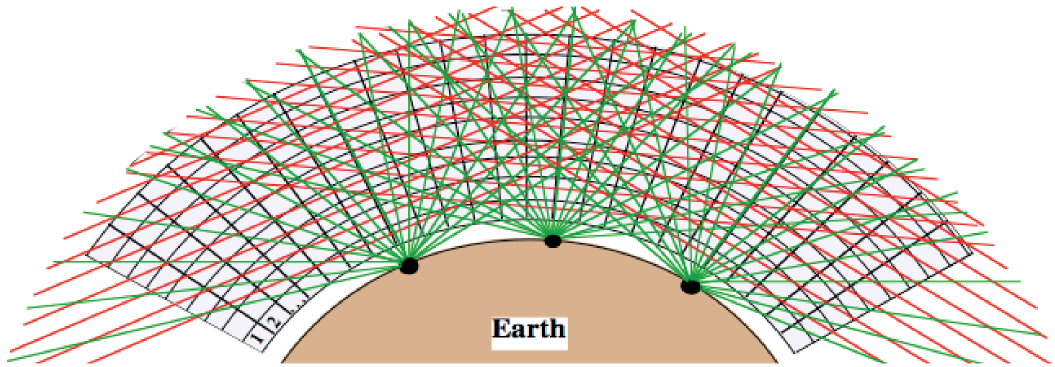
COSMIC CERTO/Tri-Band Beacon

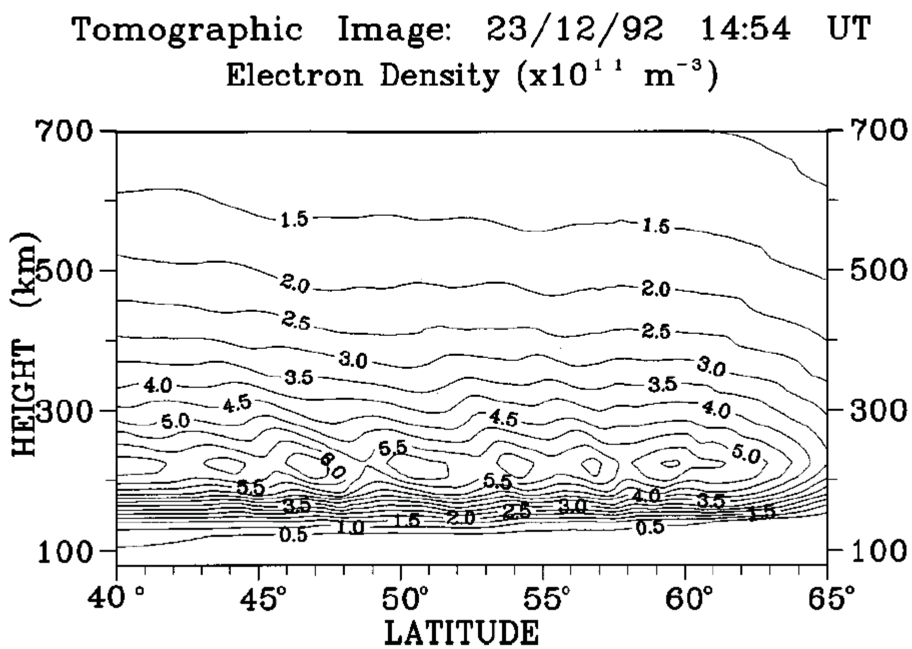
– 150 MHz, 400 MHz, 1066 $^{2}/_{3}$ MHz

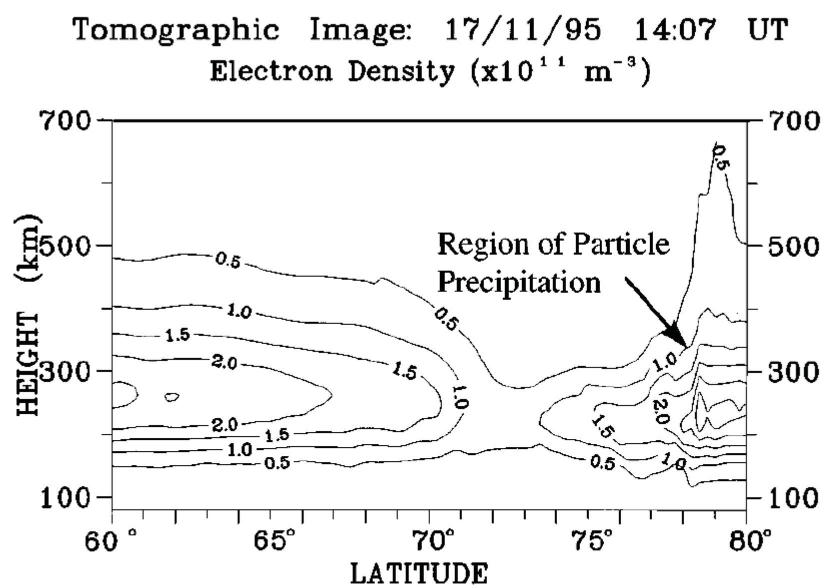


Bernhardt – COSMIC First Data User's Meeting, Boulder CO, 2006

LEO-Ground Radio Tomography

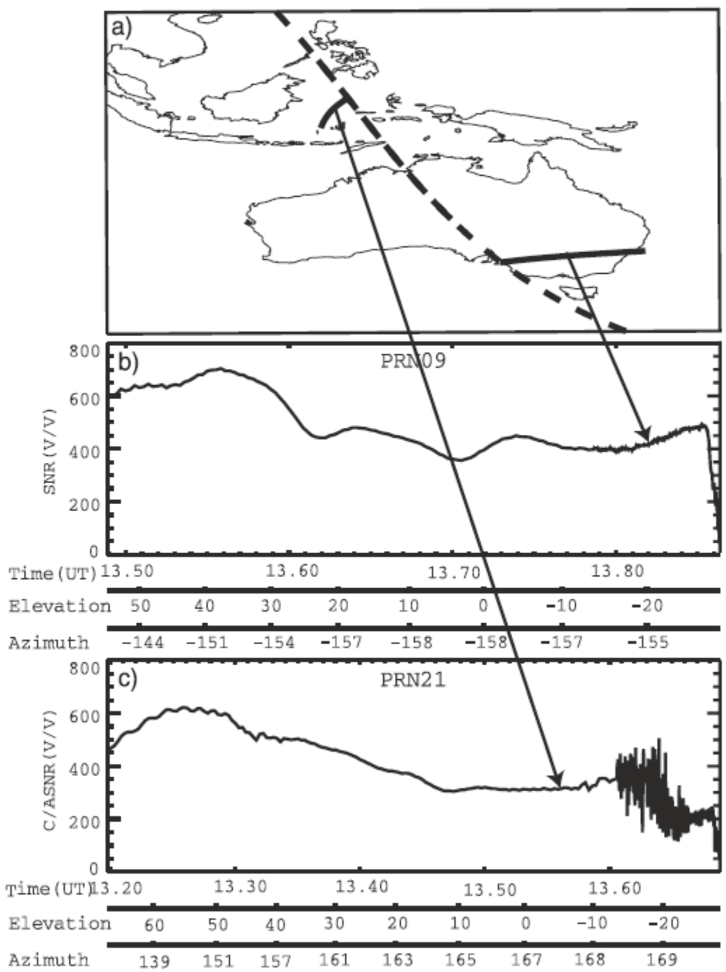


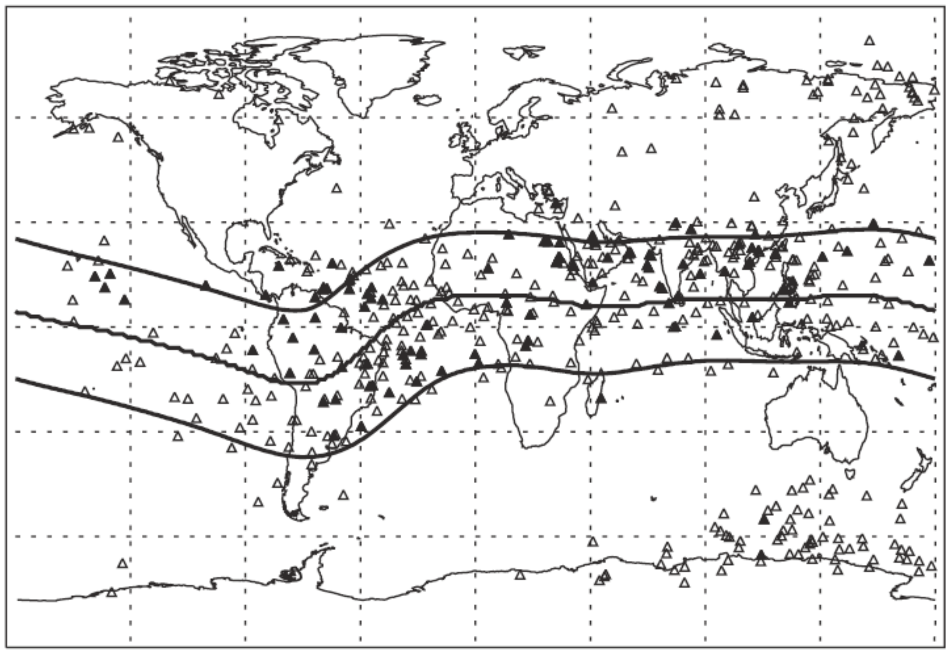




Bernhardt et al., Physics of Plasmas 1998

Irregularity Measurements

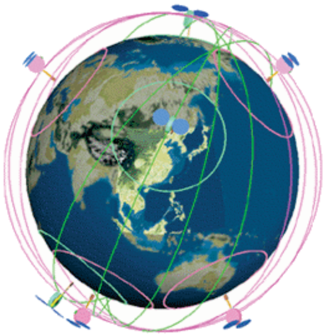


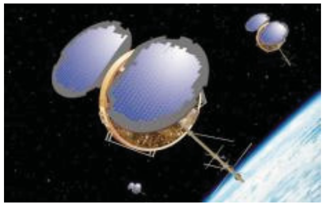


Straus, Anderson and Danaher, GRL 2003

COSMIC

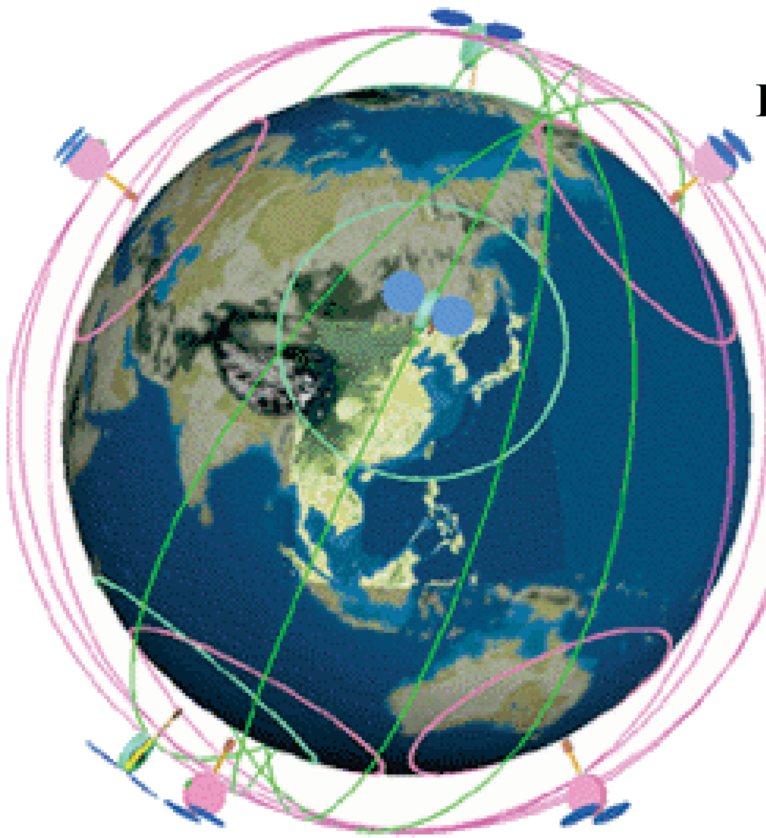
- Successful launch April 14, 2006
- Six satellite constellation
- Initial configuration: single orbital plane
- Final configuration:
  - 800 km altitude
  - Separate orbital planes
  - 72 degrees inclination
- JPL-designed receiver
- Broad-Reach Engineering built
- Near real-time feed to NOAA

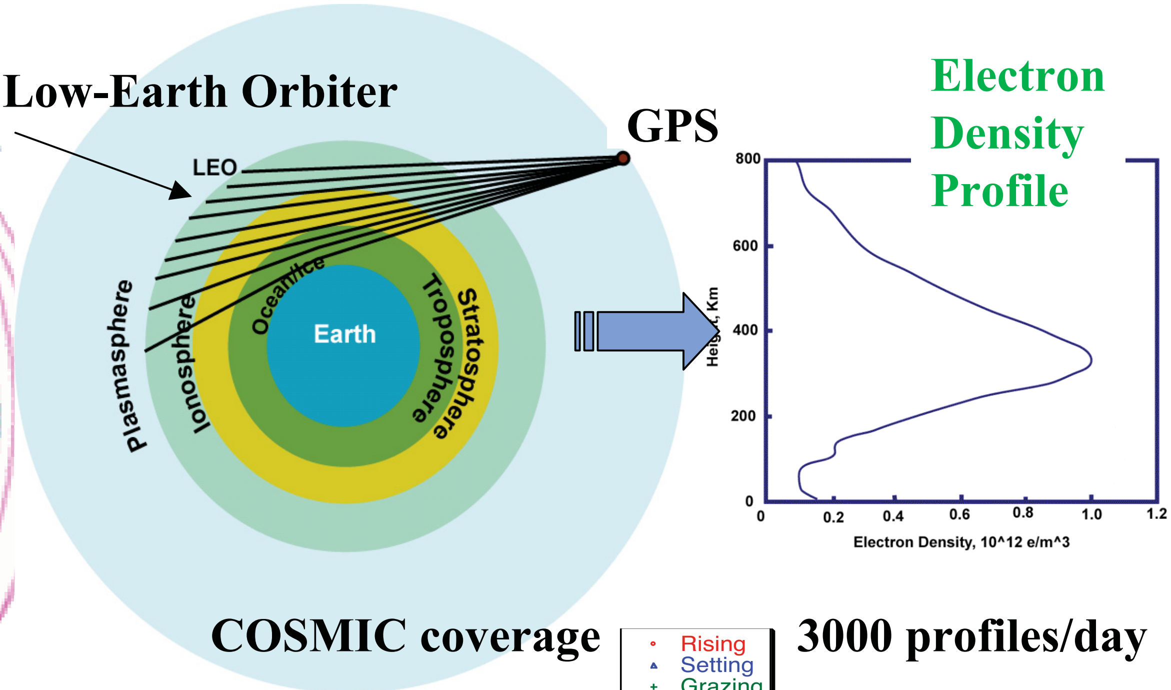




UCAR NSF NASA USAF NOAA NSPO ONR

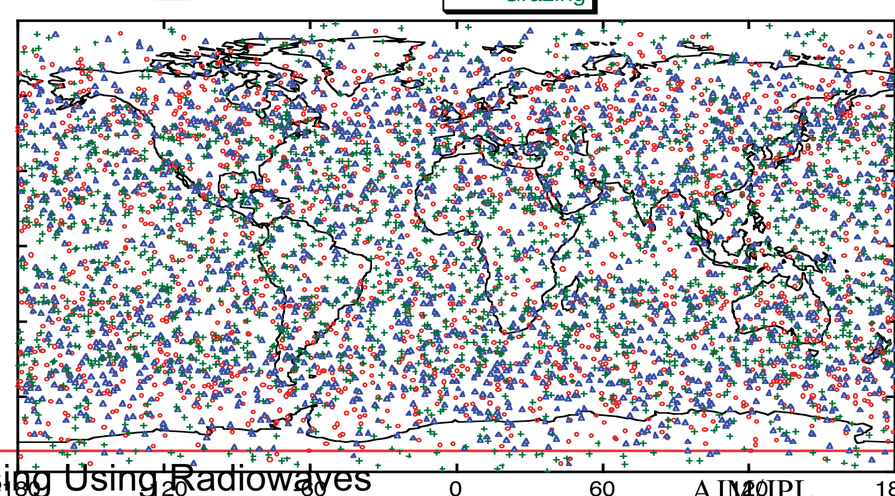
COSMIC GPS Limb Sounding: Critical Sensor Data





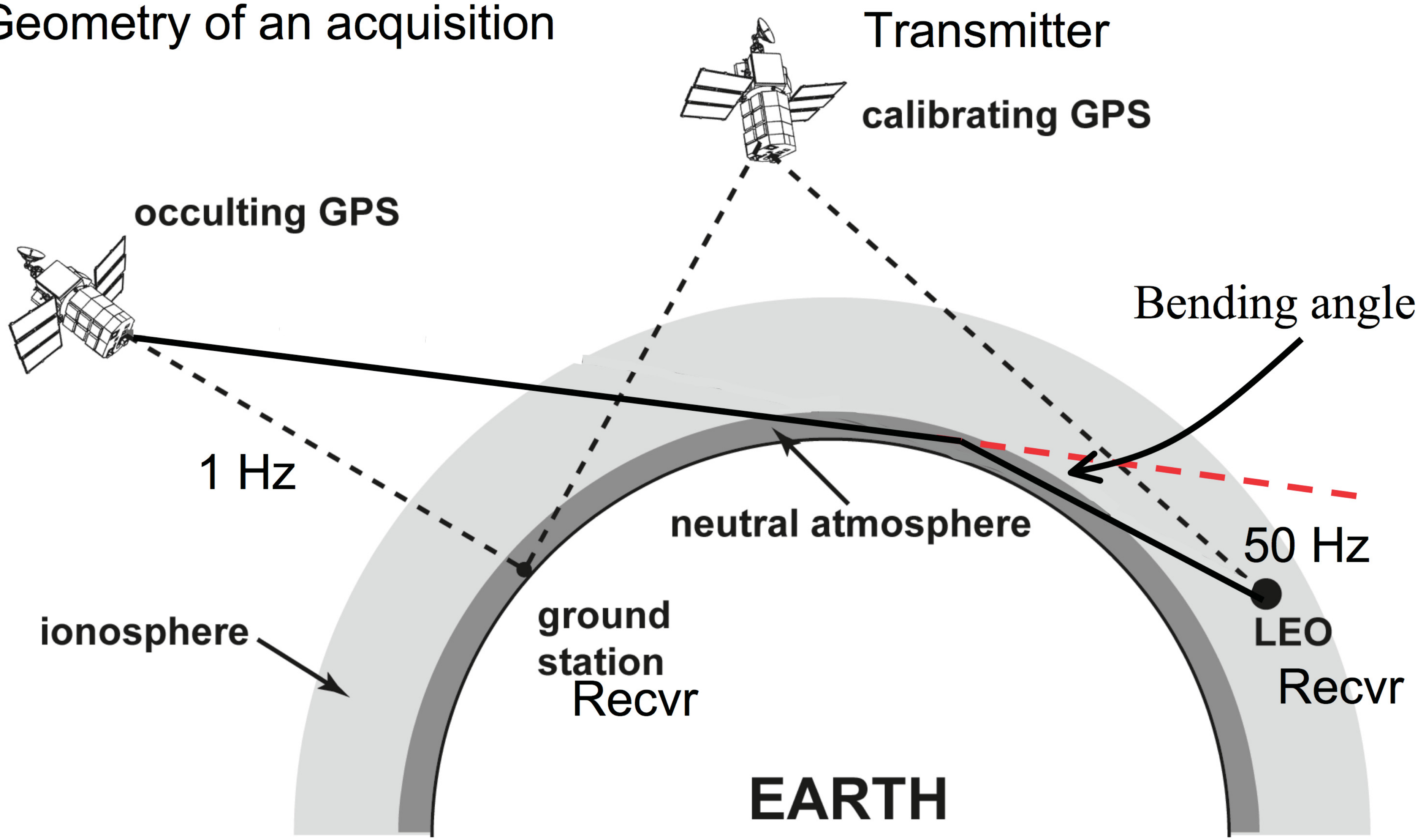
COSMIC coverage

3000 profiles/day

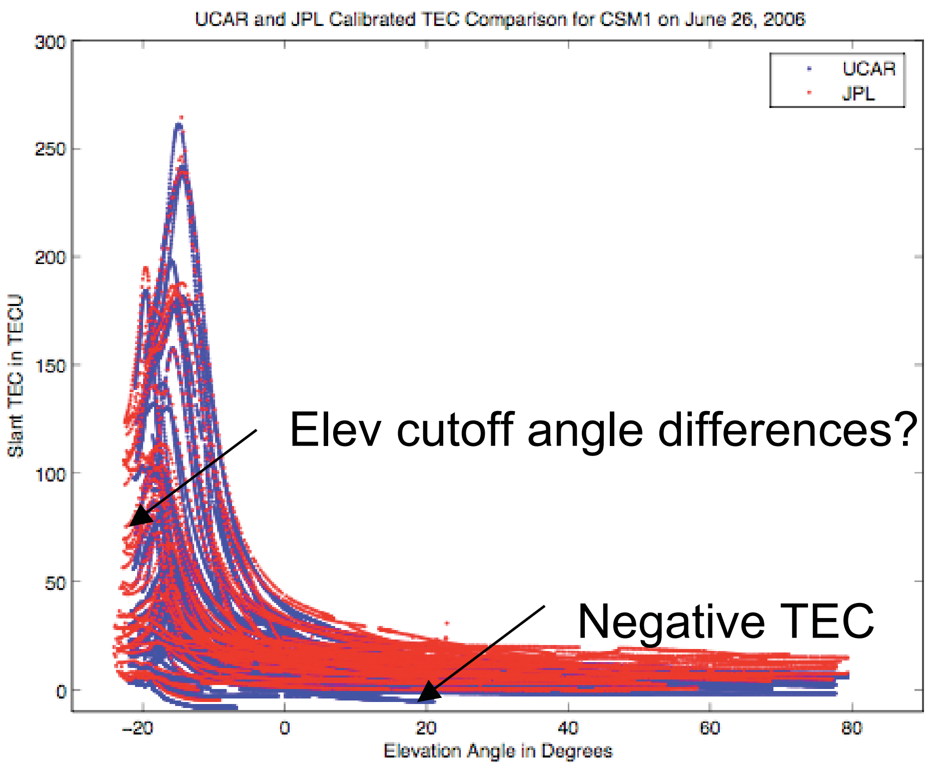


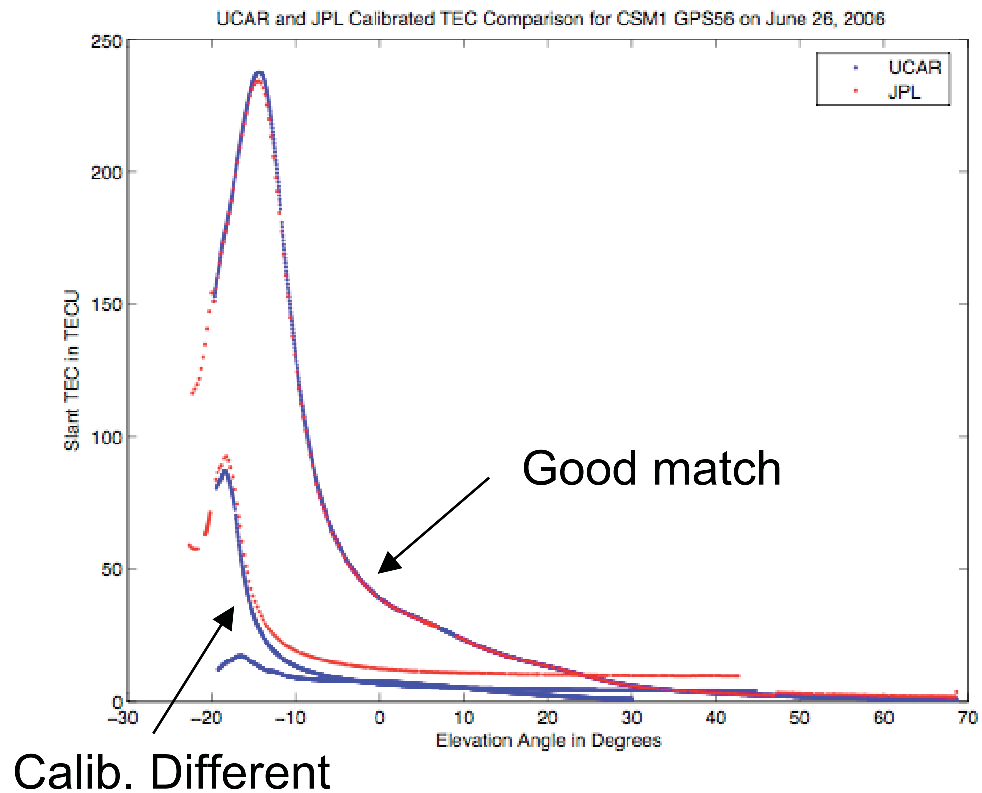
Occultation Geometry

Geometry of an acquisition



Comparison of Calibrated Slant TEC Measurements for June 26, 2006

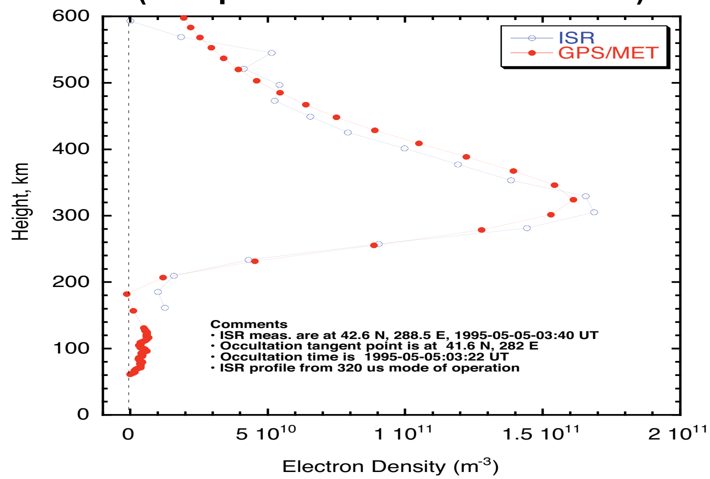




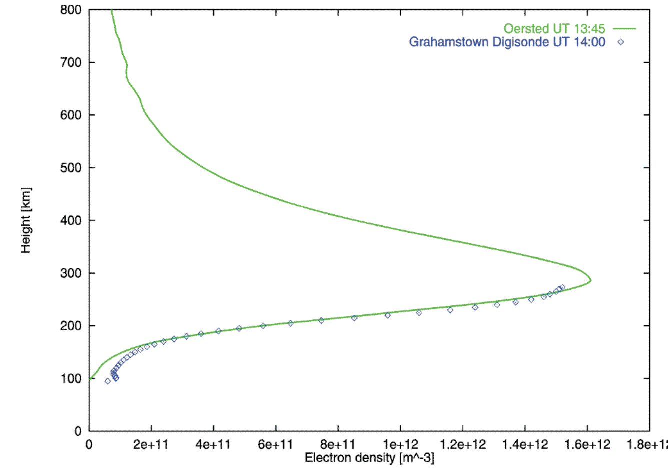
- An example of comparison of calibrated TEC between JPL and UCAR
- There appears to be a 2-3 TECU bias between JPL and UCAR slant TEC
- Negative TEC, differences between UCAR and JPL elevation cutoff angles
- Similar data volumes between JPL and UCAR

Historic examples of Abel electron density profiles

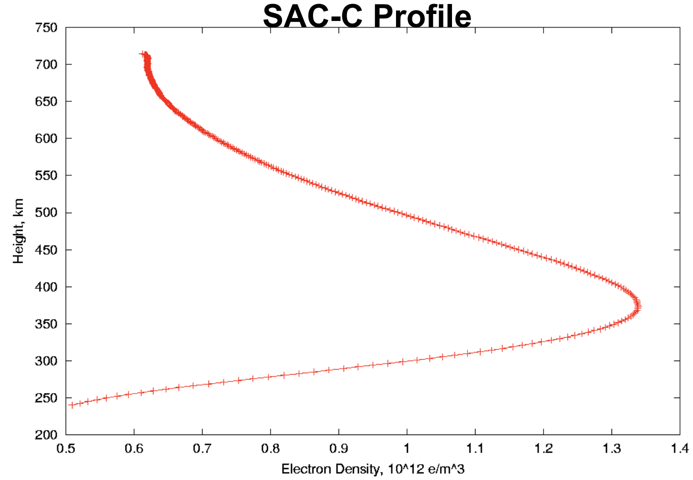
GPS/MET Profile (Compared to Millstone hill radar)



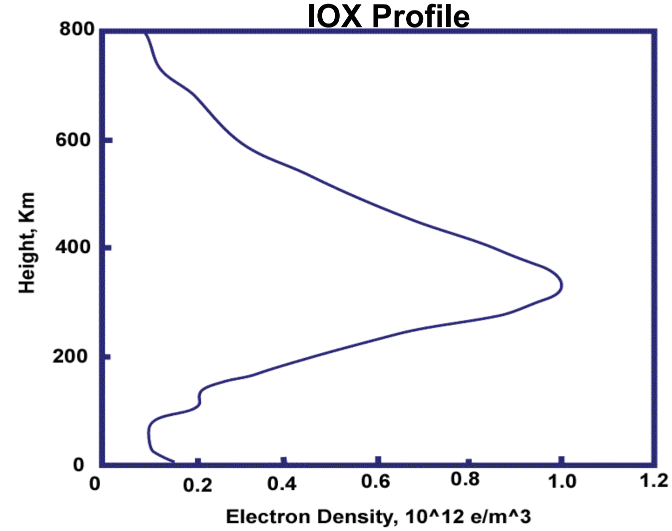
Oersted Profile (Compared to nearby ionosonde)



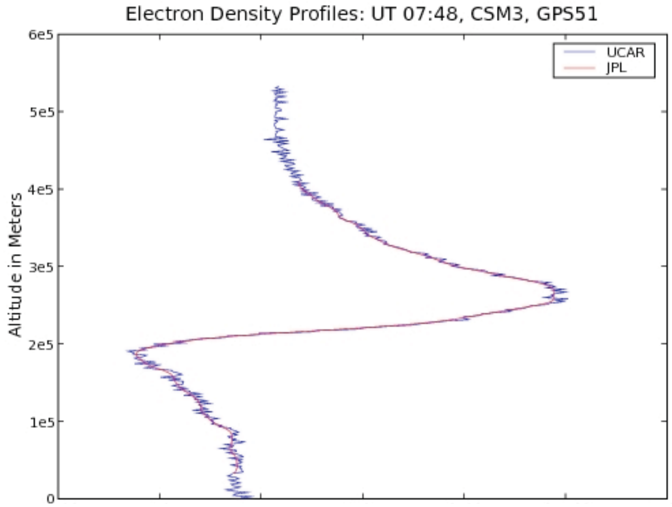
SAC-C Profile

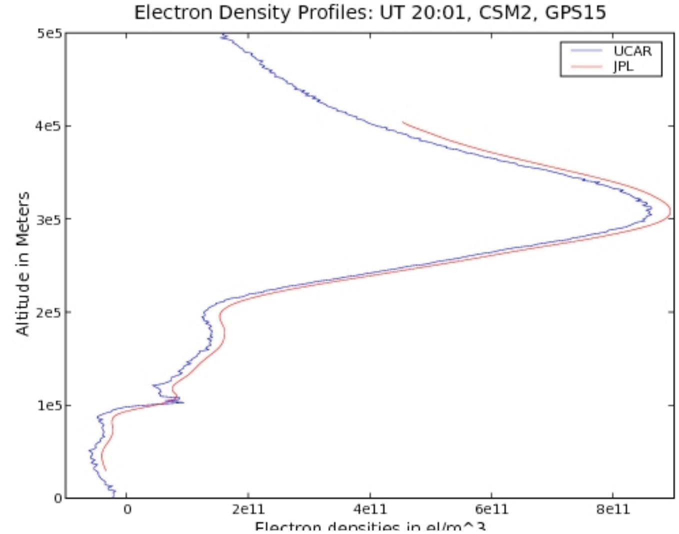


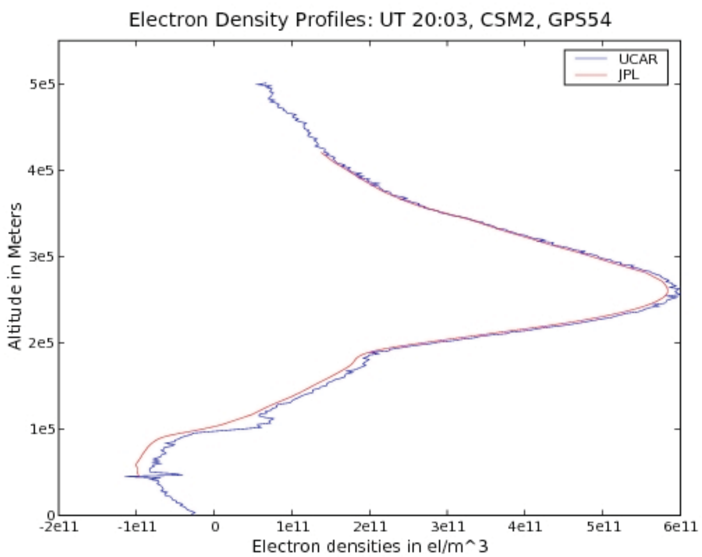
IOX Profile

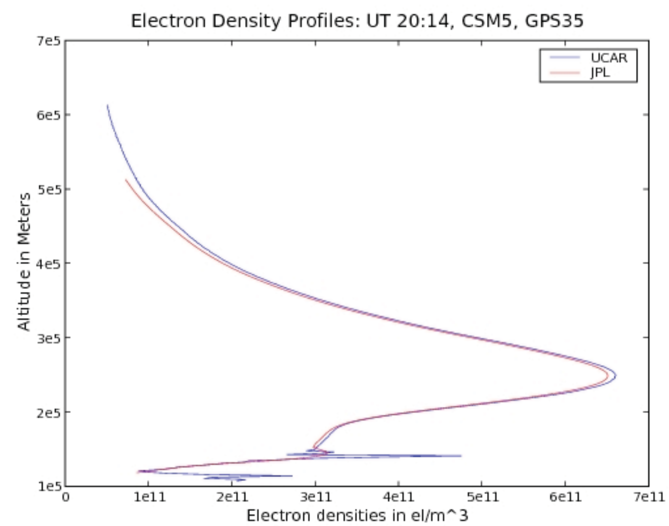


Comparison of UCAR and JPL Abel Profiles June 26, 2006



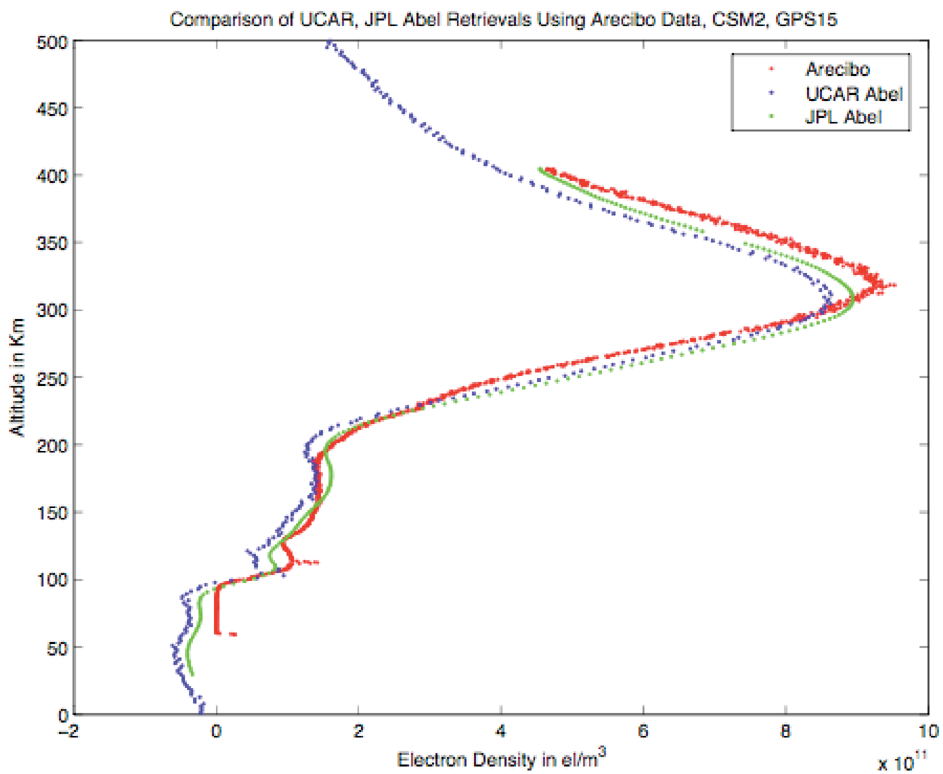


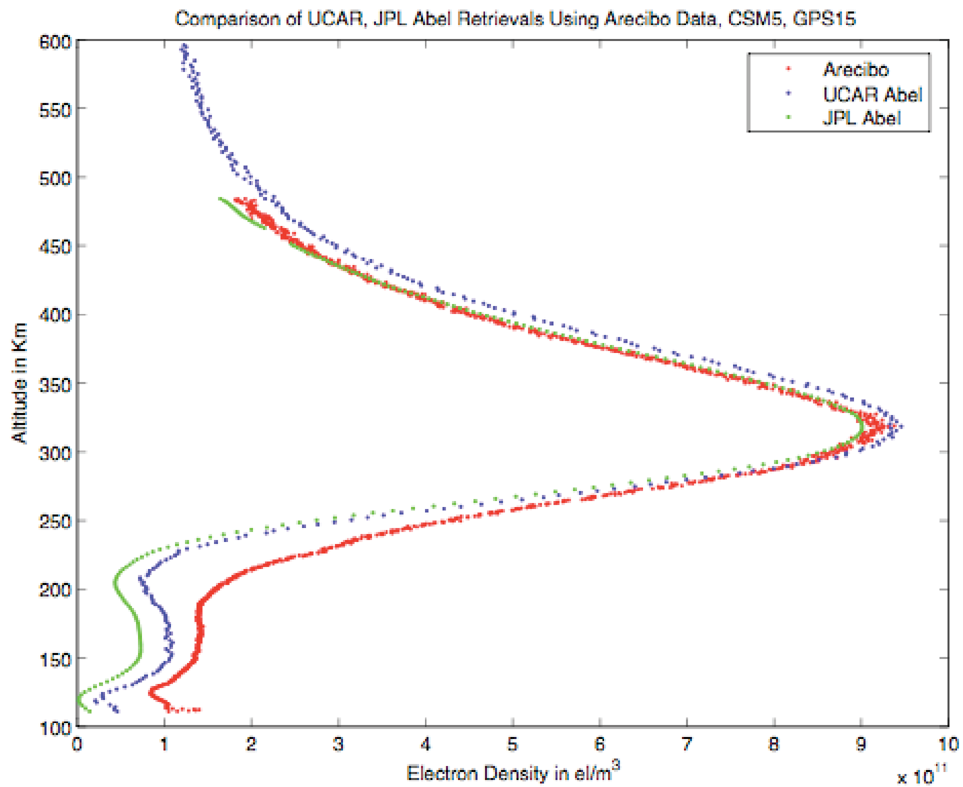




UCAR and JPL Abel profiles usually agree well

Validating UCAR and JPL Abel Profiles Using Arecibo ISR Measurements for June 26, 2006

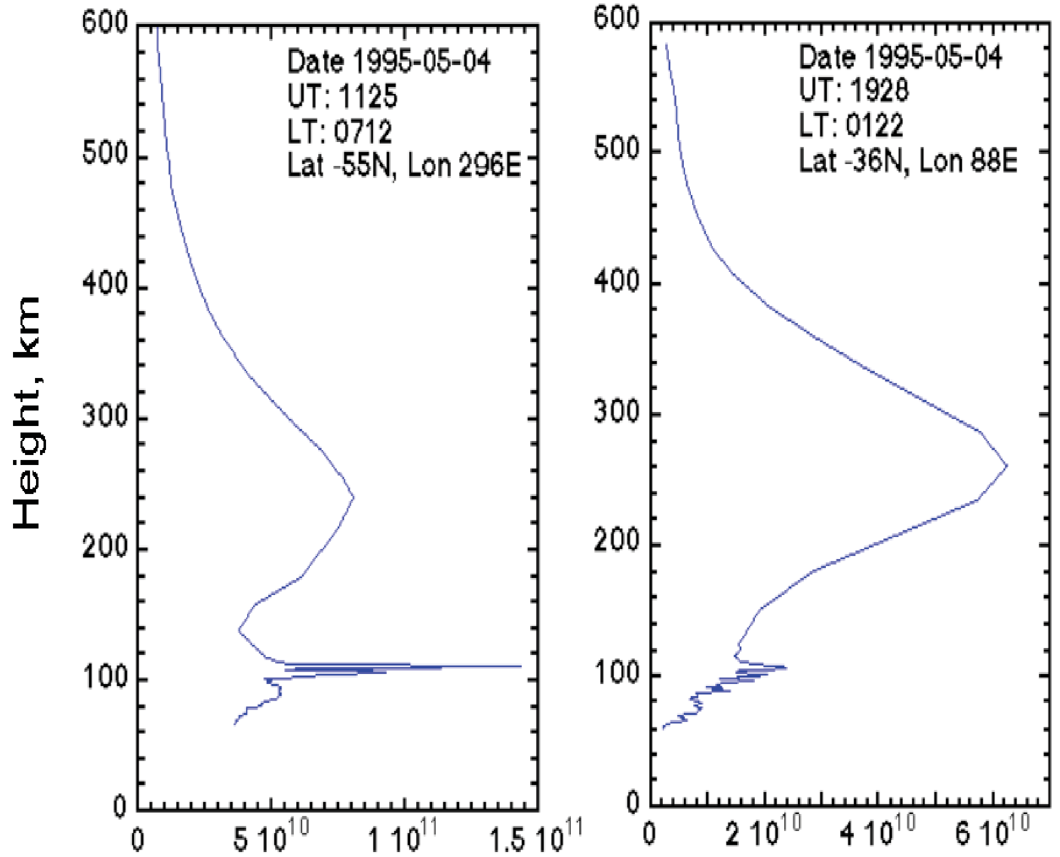




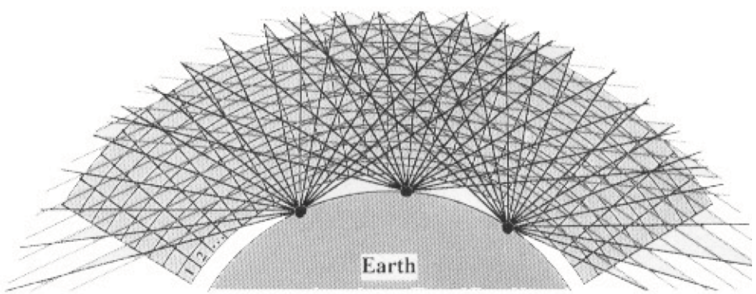
- E-region error in naive Abel profiles: negative electron densities
- Spacecraft not yet in final orbital altitudes so Abel inversions more difficult
- JPL smoothed, UCAR unsmoothed profiles

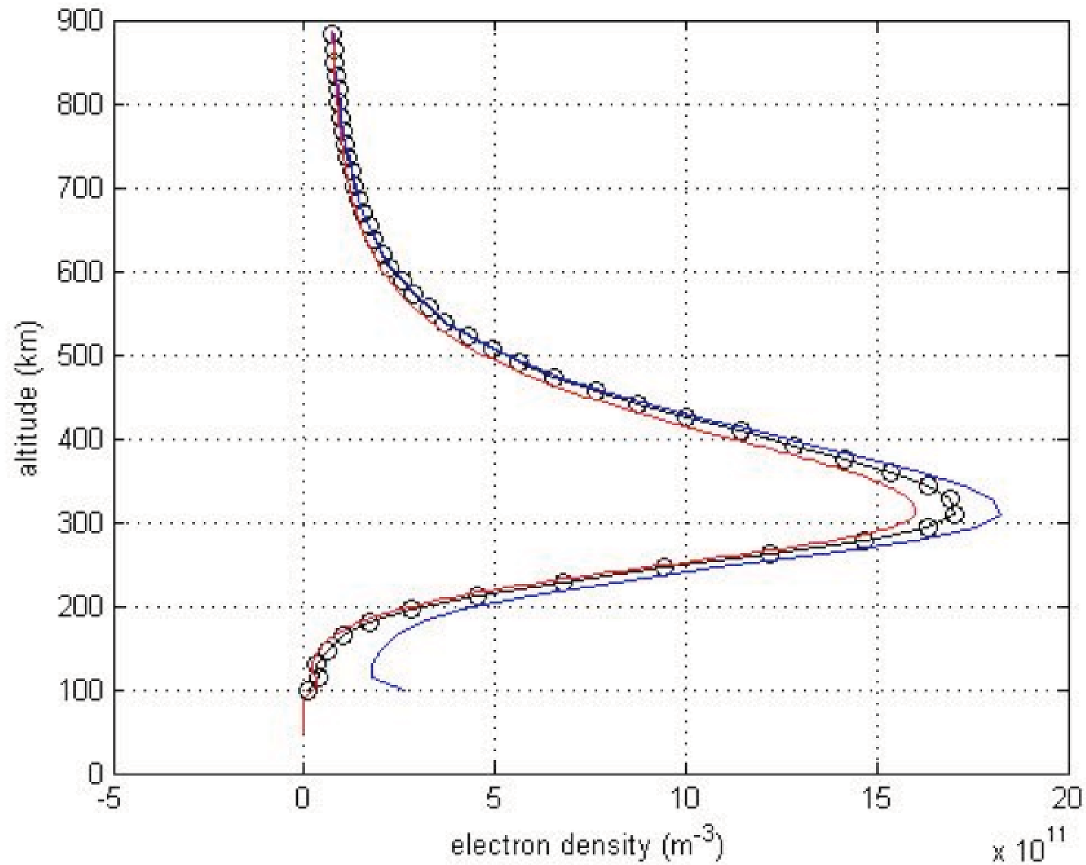
Arecibo calibrated profiles are courtesy of Prof M. Kelley and V. Wong of Cornell University

E-Region From GPS/MET 1995

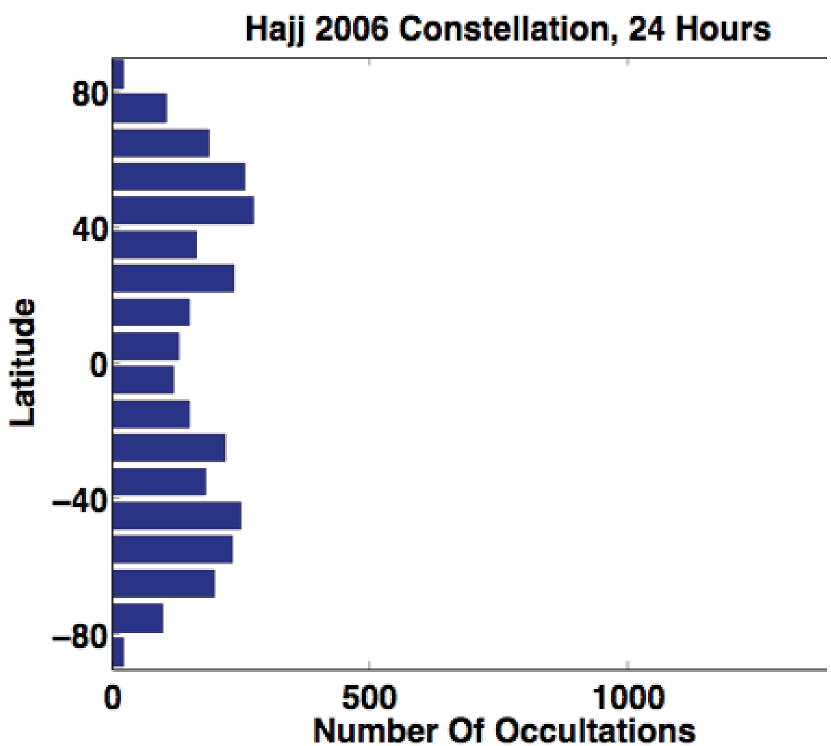


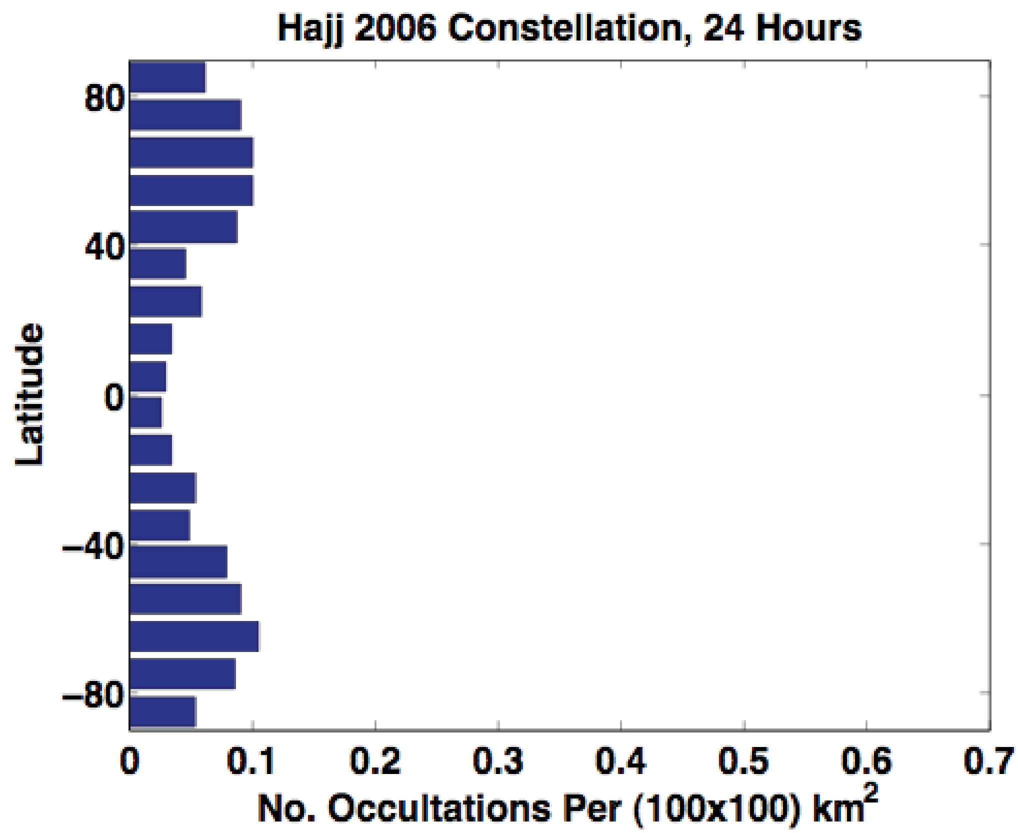
Abel Versus Gradient Assisted Retrieval



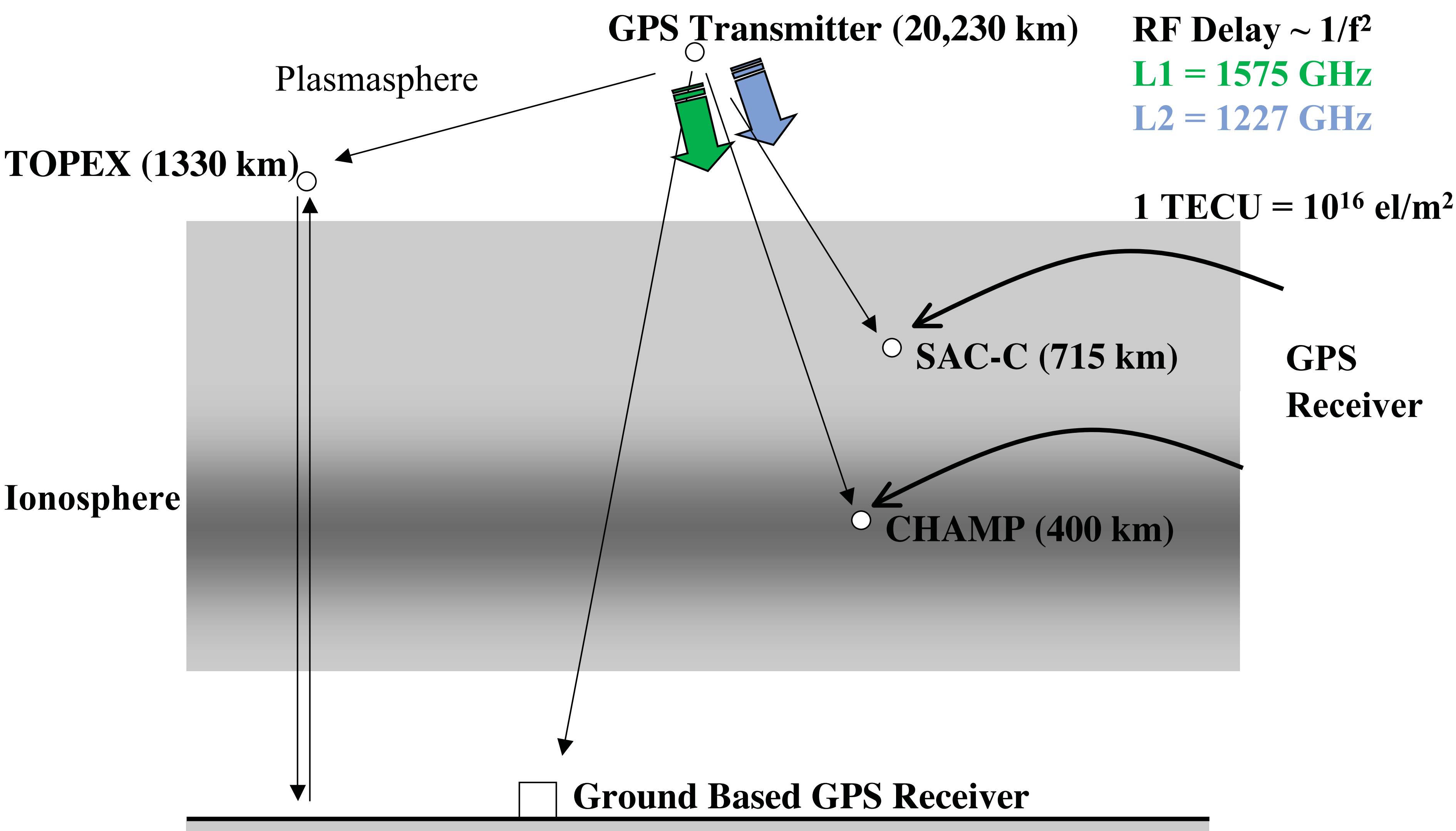


3000 Profiles/Day

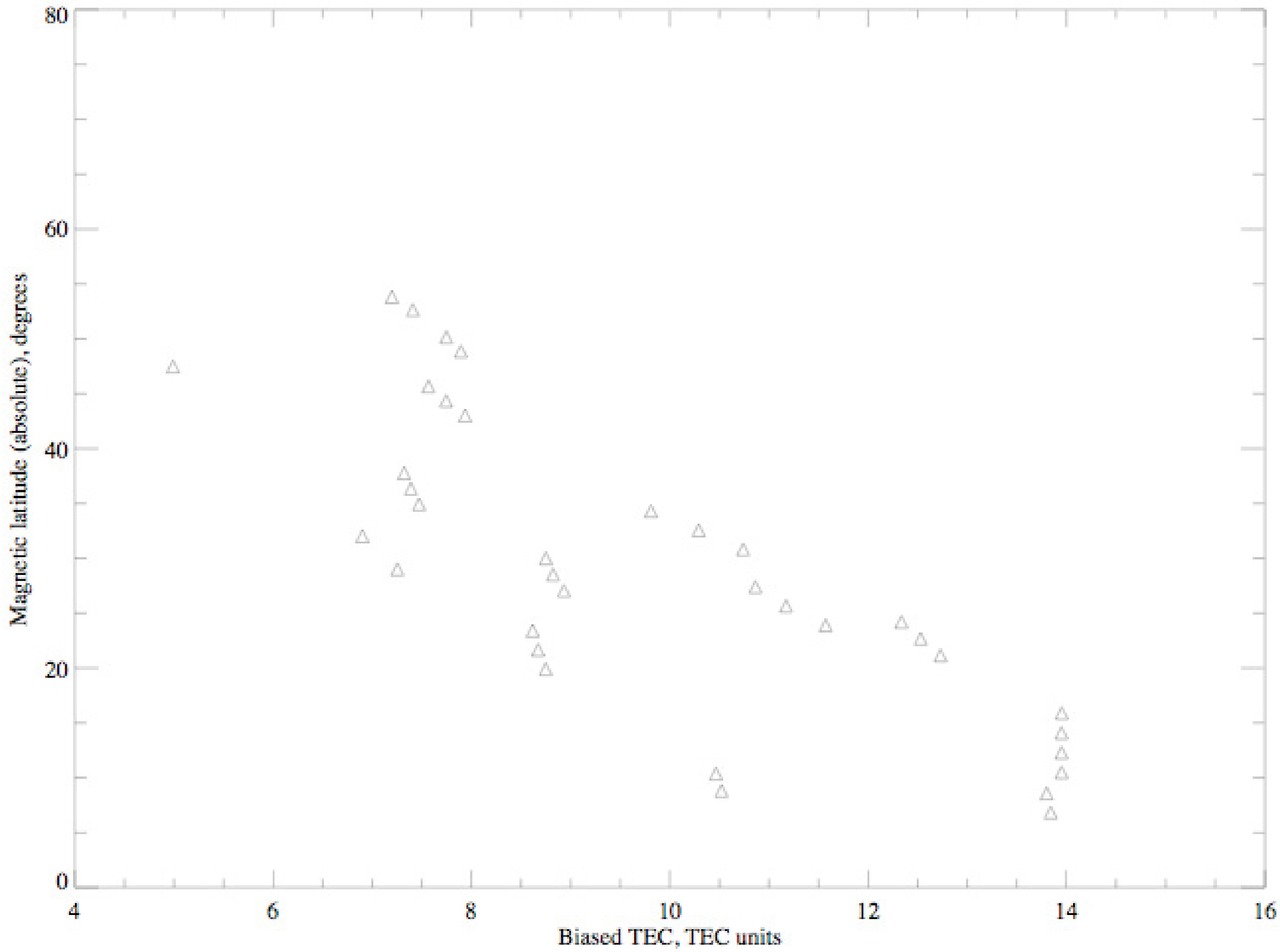




Plasmasphere

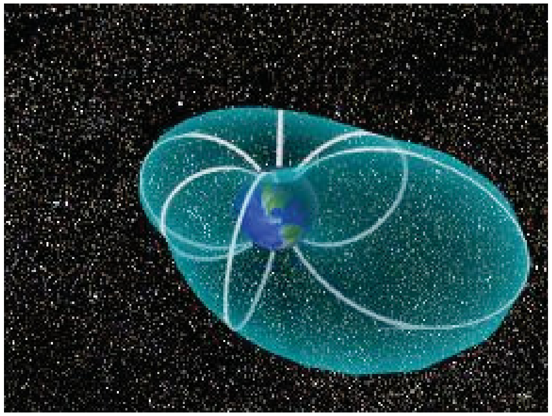


JASON TEC Above Satellite

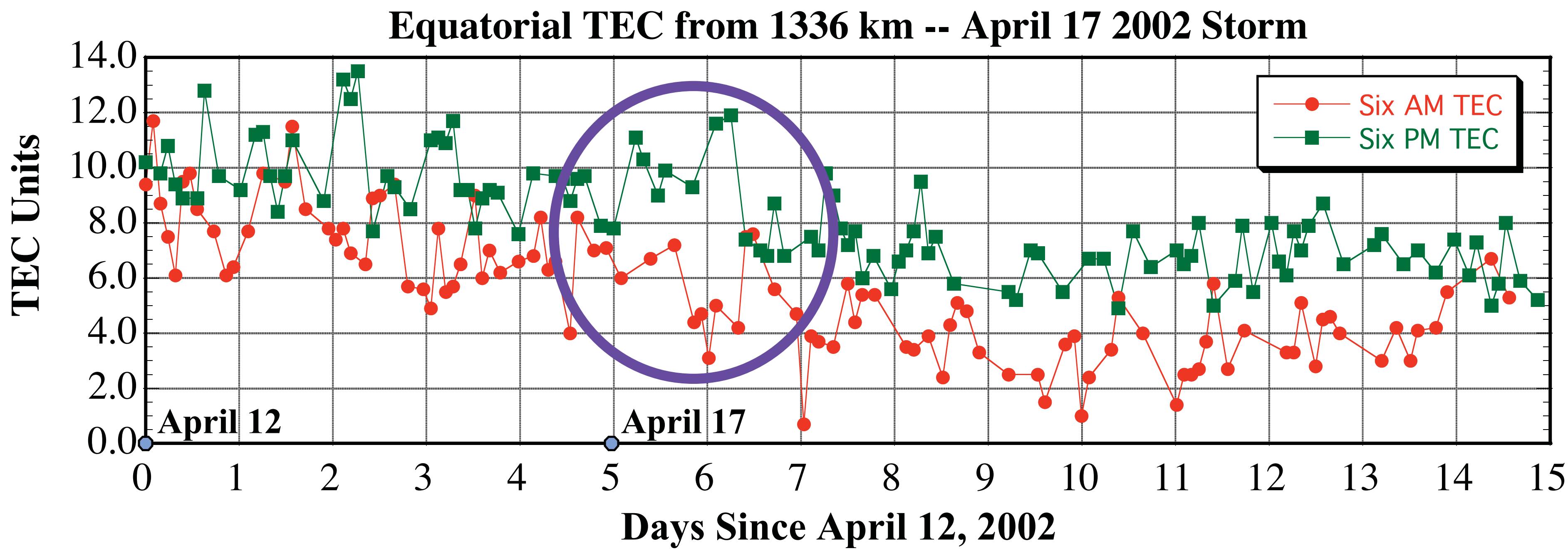


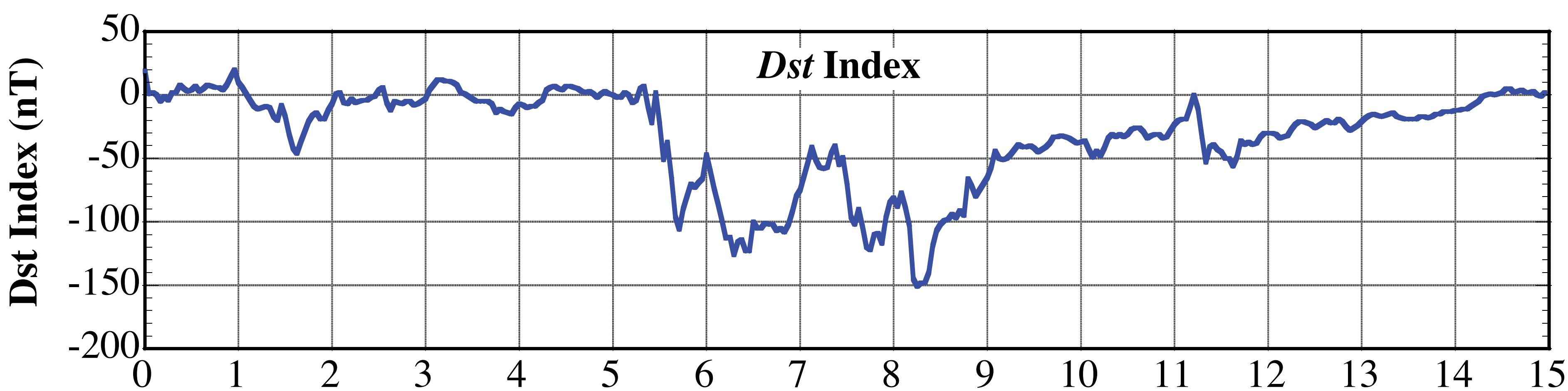
GPS Equatorial Plasmasphere Measurements

- TEC from 1336 km upward using JASON upward viewing antenna
- Blackjack receiver
- ±5 degrees in magnetic latitude
- Restricted elevation angle (> 40 deg)
- Average vertical TEC per pass in equator
- Pass repeat every 100 minutes

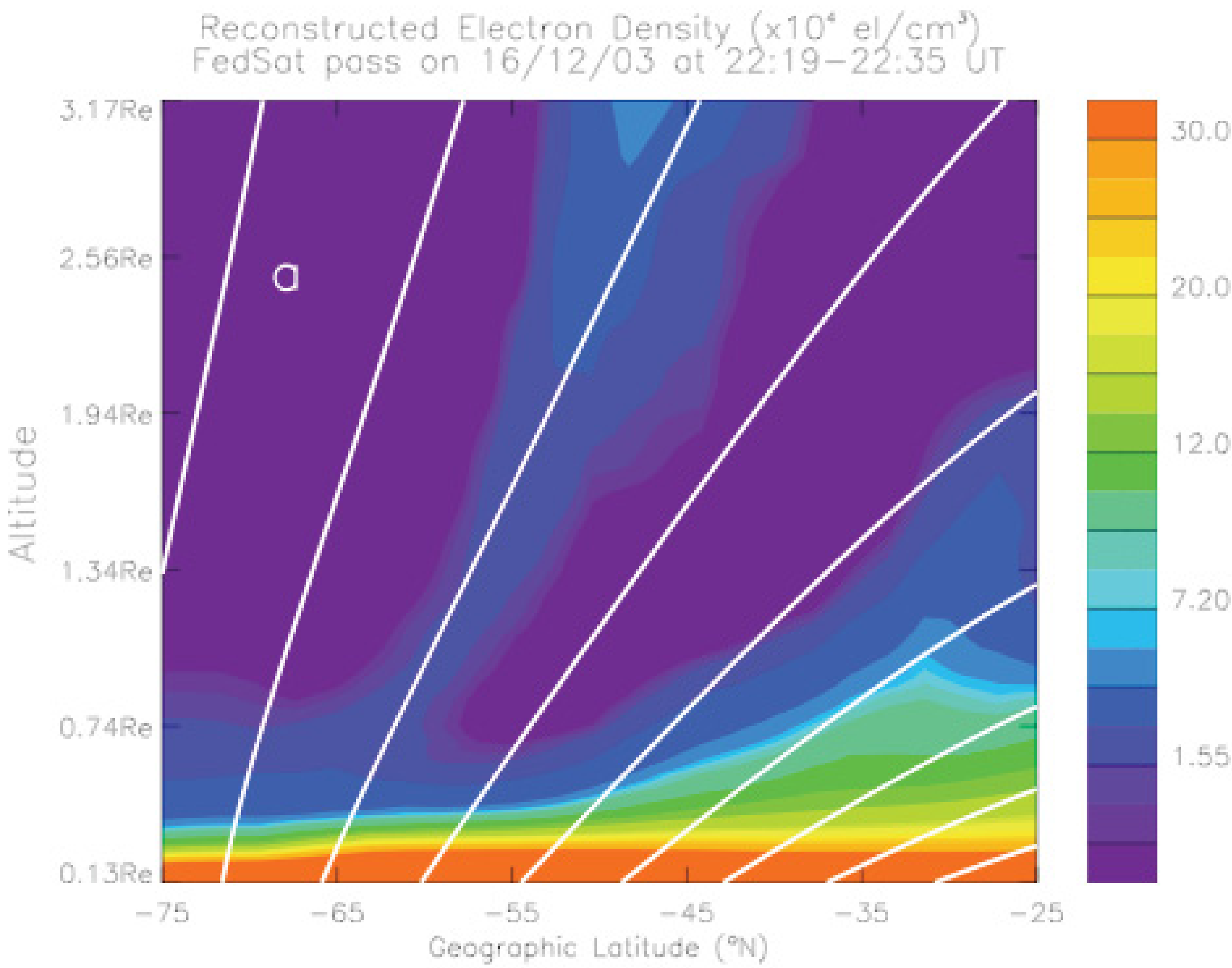


April 2002 Geomagnetic Storm





Space-based GPS Tomography



Yizengaw et al., GRL 2006

Summary

- Radio techniques have been used for decades to measure electron density
- With COSMIC and other satellites, constellation deployments likely to continue
- Instrument development: new GPS signals
  - Steerable antennas
- Algorithm development continues
  - Radiowaves a major source of data for Assimilation models
  - Improved tomographic or Abel inversions
- Advanced sounding will be covered later